HOKKAIDO UNIVERSITY

MATH SOCIAL CREATIVITY

Living Theorems in the Society

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The era of VUCA

Volatility, Uncertainty, Complexity, Ambiguity

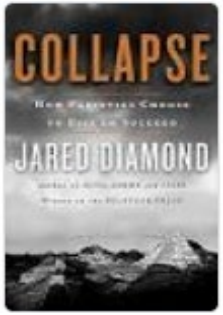
The urgent issues what we face today:

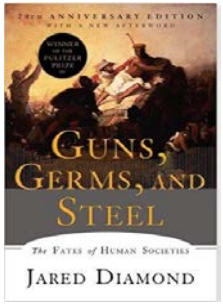
climate change, infectious diseases, biodiversity, energy, food, water, population, … and politics

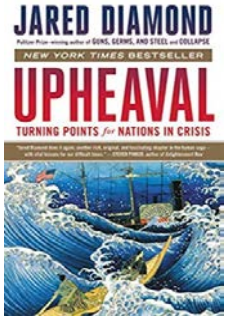
What's the origin that makes these problems so difficult?

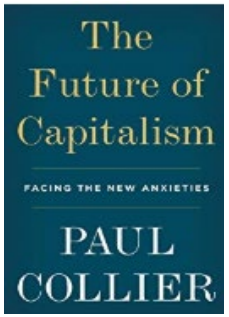
Heavily depends on our habit of thinking!

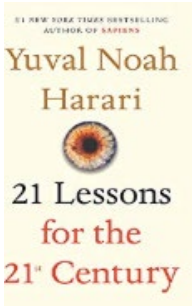
Collapse: How Societies Choose to Fail or Succeed

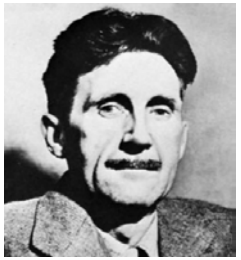












George Orwell

Jared Diamond,

Paul Collier,

Y. N. Harari

Climate change
Globalization
The class divide
The geographic divide

Forest fire

A long causal sequence: population growth ➔forest ➔soil ➔food ➔war ➔extinction

Reference
George Orwell(2008), Animal Farm, Penguin UK, ISBN-10: 9780141036137 / Jared Diamond(2011), Collapse(Revised edition), Penguin Books, ISBN-10: 0143117009
Jared Diamond(1999), Guns, Germs, and Steel(New ed): The Fates of Human Societies, W W Norton & Co Inc;ISBN-10: 0393317552
Jared Diamond(2019), Upheaval: Turning Points for Nations in Crisis, Little, Brown and Company, ISBN-10: 0316409138
Paul Colllier(2018), The Future of Capitalism: Facing the New Anxieties, Harper,ISBN-10: 0062748653 / Yuval Noah Harari(2018), 21 Lessons for the 21st Century, Jonathan Cape, ISBN-10: 9781787330870

Uncertainty comes from …

1. A dramatic increase and collision of human desires on a **limited** planet. 有限性
2. The agents that place restrictions on our way of living have shifted from visible to **invisible** things.
   不可視
   - Global warming, economic fluctuation, risk management, psychological uncertainty
3. The limitations of a simple **"cause-and-effect"** framework.
   多対多対応
   - Mutual interdependencies, multiple **feedback loops**
   - Perpetrators and victims are either the same, or difficult to distinguish.

Uncertainty comes from…

4. Dissociation of our awareness of the **scale** of space and time. スケール認知
   - We have difficulty recognizing extremely slow changes.
   - Local changes are connected to global changes.
5. Human beings think **linearly**, but the realty is **nonlinear.** 非線形性
   - We tend to think current trends will continue, but these trends could **collapse at any time**.

Make these issues "Recognizable, Interpretable, and Computable" by Mathematics!

Ref. : Y. Nishiura: The Japan Journal 6(5) 28-31 (2009)
http://www.wpi-aimr.tohoku.ac.jp/nishiura_labo/index-e.html

Functioning of Mathematics

- Recognizable
  - Visible by mathematical language
    - Mathematical modeling vs model-free approach
- Reduction
  - Compression with keeping essential features
    (avoid the curse of high-dimensionality)
    - Approximation, Topology, Dynamical system theory, Algorithm…
- Predictable
  - Manipulate computable objects in a reliable way
    - Uncertainty quantification with data assimilation




Established in 2007 and the three programs are running now!

JST Mathematical Program
PRESTO, CREST, MIRAI

Strategic Basic Research Programs

PRESTO
sakigake
CREST

JST MIRAI
JST-Mirai Program

Virtual Institute of all Mathematics “Beyond discipline”

Living Theorems

Case study

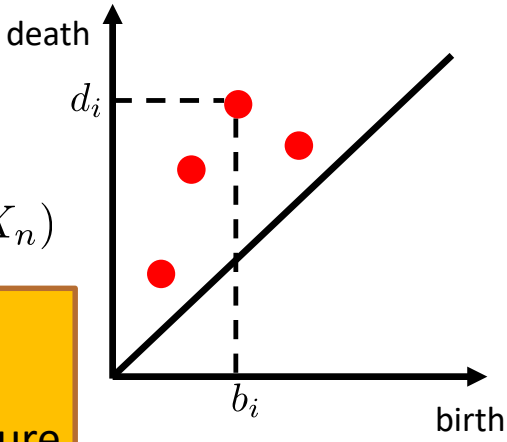
Theorem + Software +Applications

WG2,4,6

Persistent homology

Persistent homology

Hiraoka

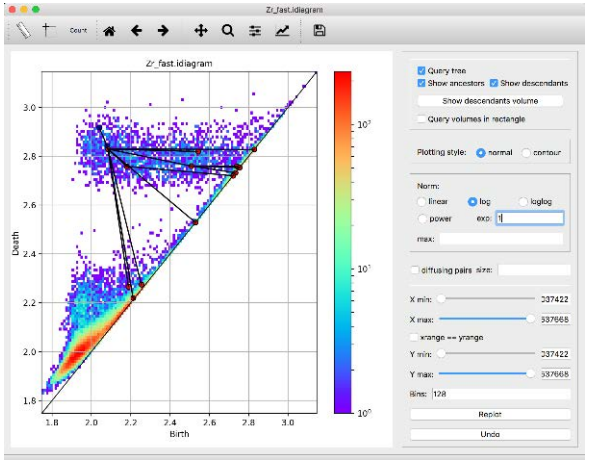


Persistence diagram (PD)

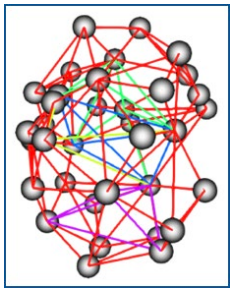
- Multiscale input data: $\mathcal{X} : X_1 \subset X_2 \subset \cdots \subset X_n$
  (e.g., atomic configuration, gene expression, digital image)
- Persistent homology: $H_\ell(\mathcal{X}) : H_\ell(X_1) \to H_\ell(X_2) \to \cdots \to H_\ell(X_n)$
- Theorem (Gabriel): $H_\ell(\mathcal{X}) \simeq \bigoplus_{i=1}^{s} I[b_i, d_i]$
  ⇒ Each interval expresses birth/death of a topological feature
- Theorem (Escolar and Hiraoka): The inverse of $I[b, d]$ is uniquely solvable.
  ⇒ Inverse analysis
- Software (Obayashi): HomCloud computes PDs efficiently + inverse analysis and machine learnings
  ⇒ Spread of the methods to the society

Obayashi

HomCloud

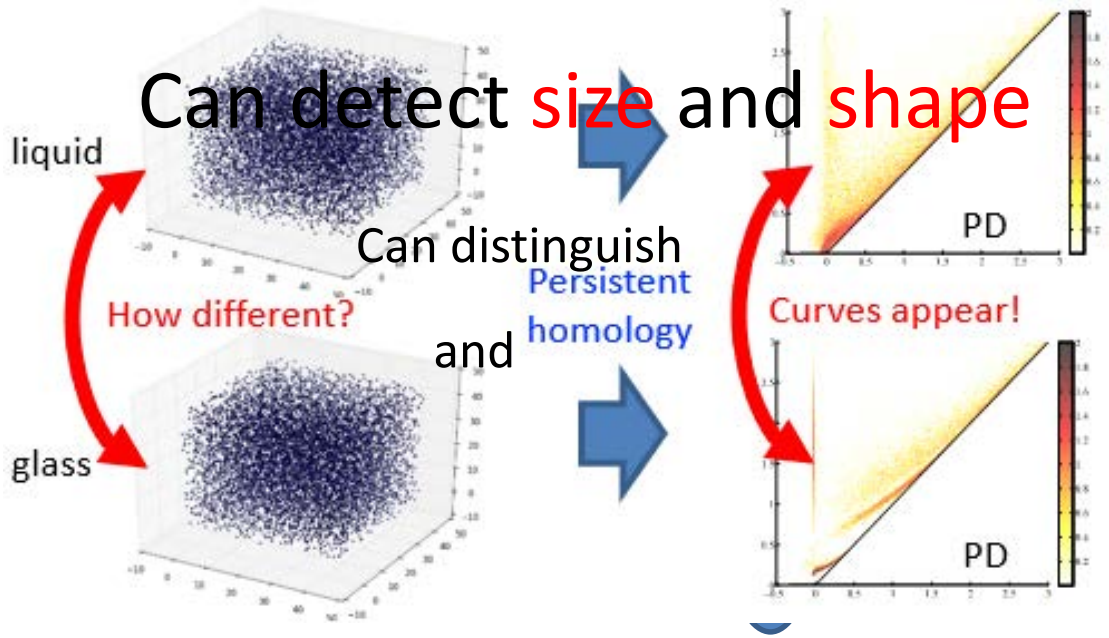


Inverse analysis



Data set ⇨ **Persistent diagram (almost 2D)**

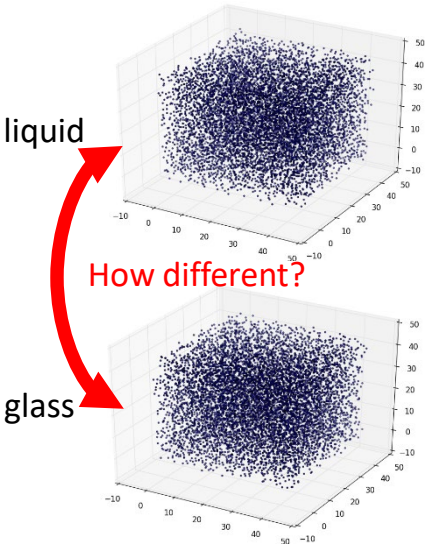
(connectivity, ring, cavity)



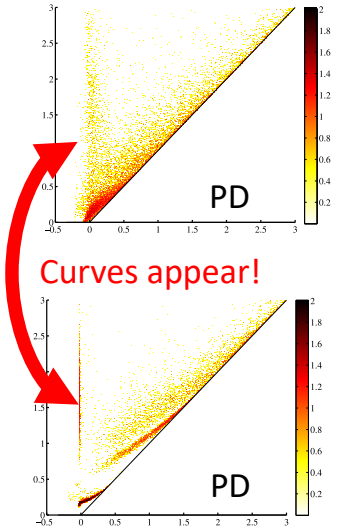
A new non-invasive mathematical method of measurement with huge reduction

Application

- Glass structural analysis (Hiraoka et al, PNAS 2016)

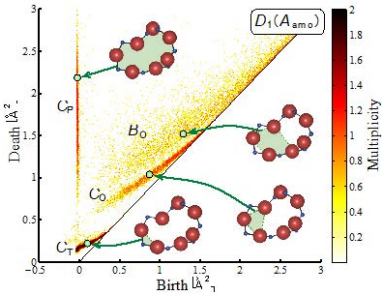


Persistent homology

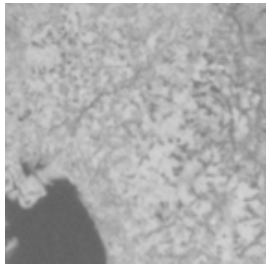


- Existence of curves uncovers hidden geometric structures only embedded in glass
- The curves also identify materials properties (rigidity)
- Inverse analysis explicitly shows hierarchical ring structures

Inverse analysis

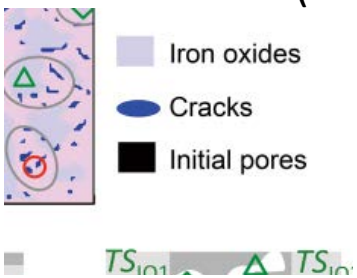


- Crack identification in iron-ore sinter (Kimura et al, Scientific report 2018)



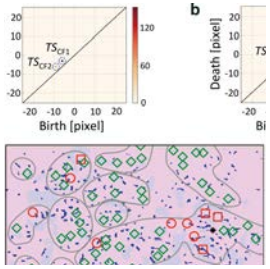
Sintering images

Persistent homology



PD machine learning

Inverse analysis



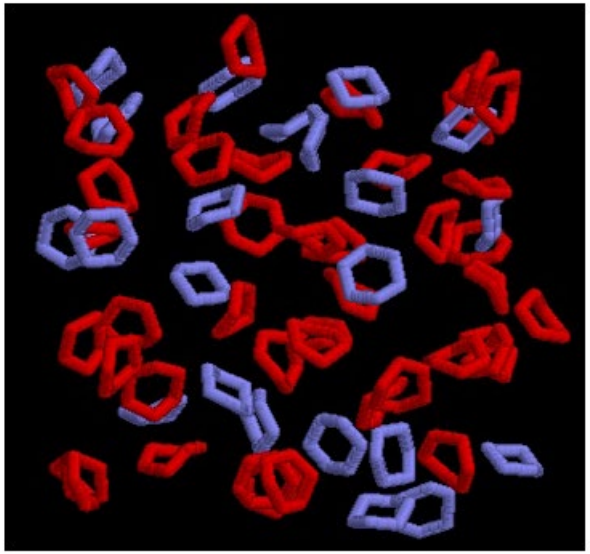
Prediction of cracks

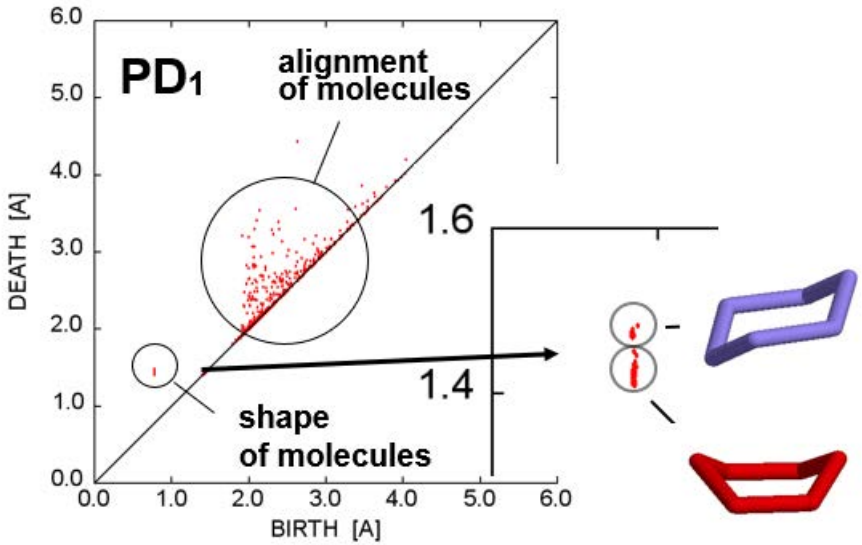
- PD enables efficient learnings than conventions
- Crack locations are predicted
- Many collaborations with companies

Cyclohexane conformation
Chair or Boat?

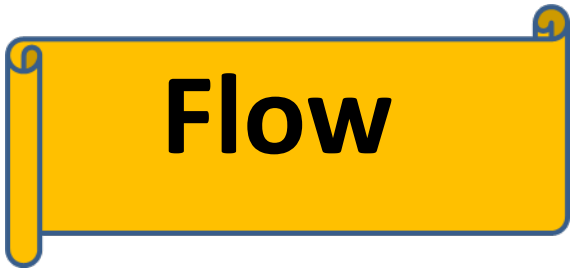
Akagi (Tohoku Univ.)

PD can detect the difference **automatically**!





1. Calculate PD of the whole system
2. Find specific groups of generators
3. Reduce the generators to the atomic positions



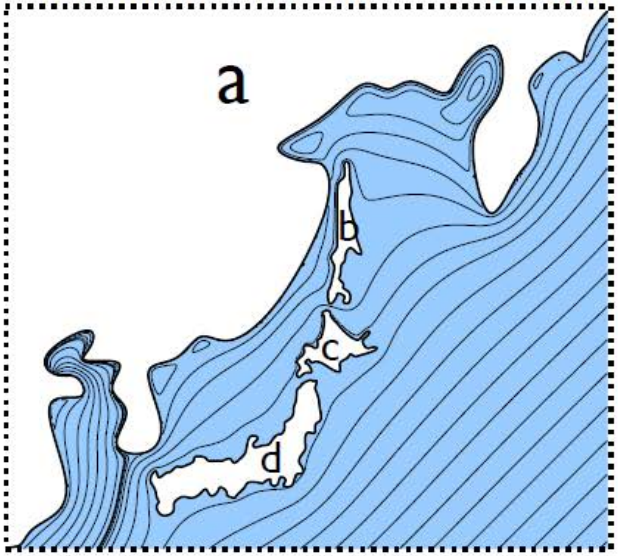
WG 4, 5

Topological Flow Data Analysis (TFDA)

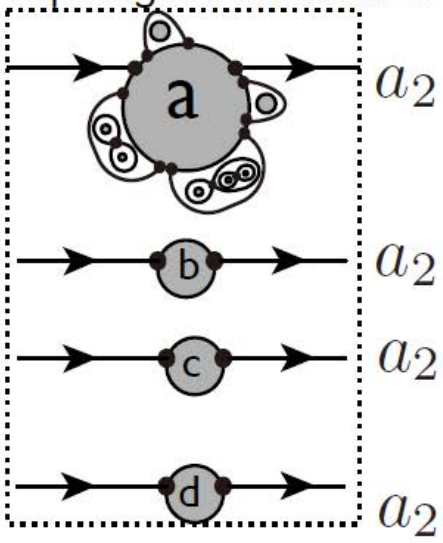
COT (partially Cyclically Ordered rooted Tree) representation

Example and Uniqueness

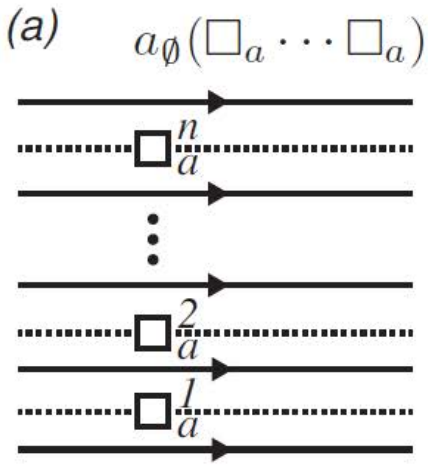
Streamlines in the sea of Japan



Topological structures



Fundamental structure



There are four a_2 orbit structures, three of which has no internal structure.

$$a_\emptyset(a_2, a_2, a_2, a_2(\square_{c_+} \cdots \square_{c_+}, \square_{c_-} \cdots \square_{c_-}))$$

The a_2 orbit has four class-c orbit structures, two of which have no internal structures.

$$a_\emptyset(a_2, a_2, a_2, a_2(c_+(\square_{b_+}), c_+(\square_{b_+}), c_+(\sigma_+), c_-(\sigma_-)))$$

Embedding more class-b orbit structures, we obtain the COT representation.

$$a_\emptyset(a_2, a_2, a_2, a_2(c_+(b_{++}\{\sigma_+, \sigma_+\}), c_+(b_{++}\{b_{++}\{\sigma_+, \sigma_+\}, \sigma_+\}), c_+(\sigma_+), c_-(\sigma_-))$$

Threorem. (S-, Yokoyama '18) Every structurally stable Hamiltonian vector fields with/without uniform flow is one-to-one correspondence with a unique COT representation.

TFDA: Theory and Software

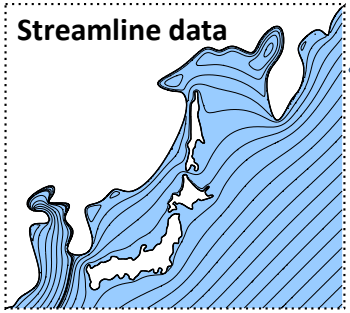

Sakajo


Yokoyama

PRESTO sakigake CREST JST MIRAI JST-Mirai Program

Tree representation theorem (Yokoyama & Sakajo, '18)

Theorem. Every structurally stable Hamiltonian vector with/without uniform flow is one-to-one correspondence with COT representations



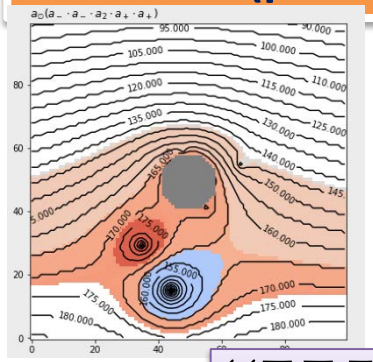
COT (partially Cyclically Ordered rooted Tree representation

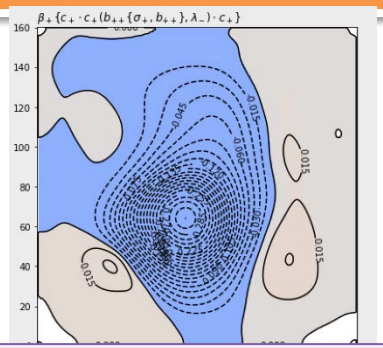
$$a_\emptyset(a_2, a_2, a_2, a_2(c_+(b_{++}\{\sigma_+, \sigma_+\}), c_+(b_{++}\{b_{++}\{\sigma_+, \sigma_+\}, \sigma_+\}), c_+(\sigma_+), c_-(\sigma_-))$$

Flow $\Longleftrightarrow$ Word

nted by a **unique** symbolic nguage for interdisciplinary studies of flows.

Software (psiclone), converting flow data to COT via TDA

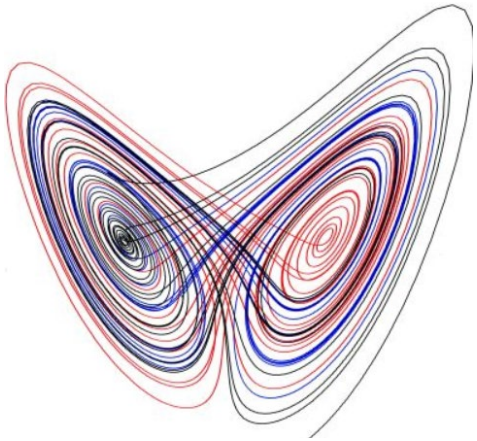




A large amount of flow evolution data are reduced to a small size of COT symbols.
(0) Drastic data compression
(1) Qualify/Quantify latent knowledge behind flow data.
(2) Predict future transitions without exception.

"Word" pops-up in a second!

Chaotic dynamics ➔ Symbolic dynamics



$$\frac{dx}{dt} = \sigma(y - x)$$

$$\frac{dy}{dt} = x(\rho - z) - y$$

$$\frac{dz}{dt} = xy - \beta z$$

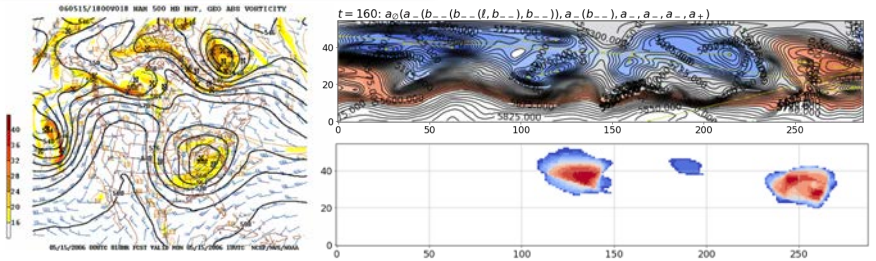
$$\ldots x_{-2} x_{-1} . x_0 x_1 x_2 \ldots,$$

Flow dynamics ➔ Word dynamics

(Infinite dim)

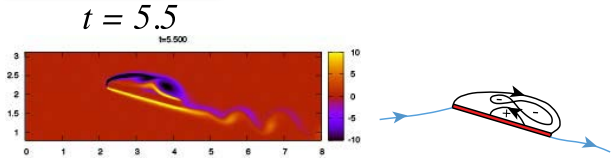
Applications

Geo-science/environments



Identification of “Blocking phenomena”

Engineering

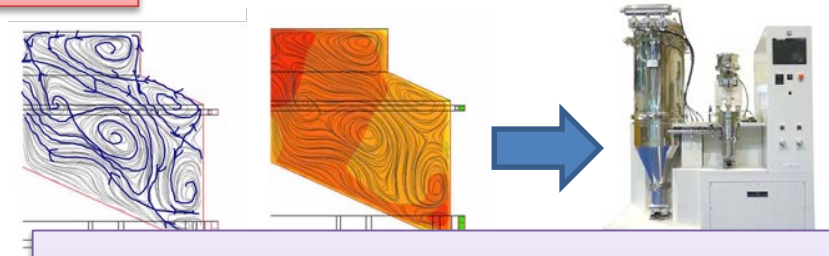


$$a_\emptyset(a_2(\lambda_+, c_-(b_{--}\{\sigma_-,\sigma_-\}, c_+(\sigma_+,\lambda_-))))$$

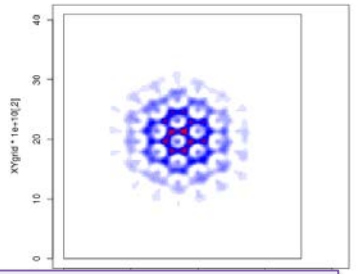
A new concept of an efficient wing design

TFDA

Industry



Medical data
Material data
Car design data
Human flow data



Drastic data compression
Qualify/Quantify latent knowledge behind flow data.
Predict future transitions without exception

WG 1, 4, 5

Integrable system

Crowd control

Nishinari

PRESTO sakigake

JST MIRAI

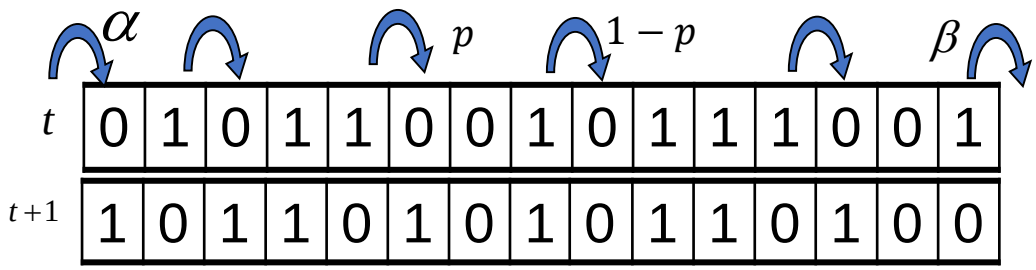
JST-Mirai Program

ASEP: a simple model for Pedestrians

ASEP(Asymmetric Simple Exclusion Process)

=1D motion of pedestrians

Rule : move forward if the front is empty

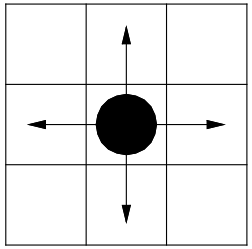


This is an exactly solvable model, i.e., we can Calculate flux in the stationary state.

Evans, et al. J. Phys A: Math. Gen. 26 (1993) 1493

Floor Field model

=2D version of ASEP



0	$p_{-1,0}$	0
$p_{0,-1}$	$p_{0,0}$	$p_{0,1}$
0	$p_{1,0}$	0

Probability of moving to each cell

$$p_{ij} \approx \exp(k_D D_{ij}) \exp(-k_s S_{ij})$$

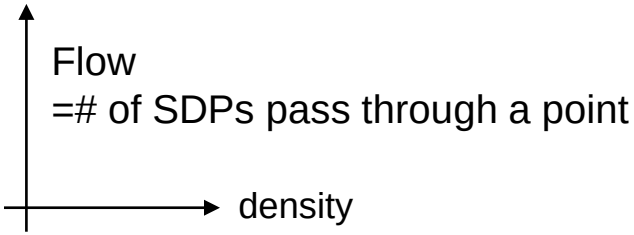
S_{ij} Distance between the cell (i,j) and a door

D_{ij} Number of footprints at the cell (i,j)

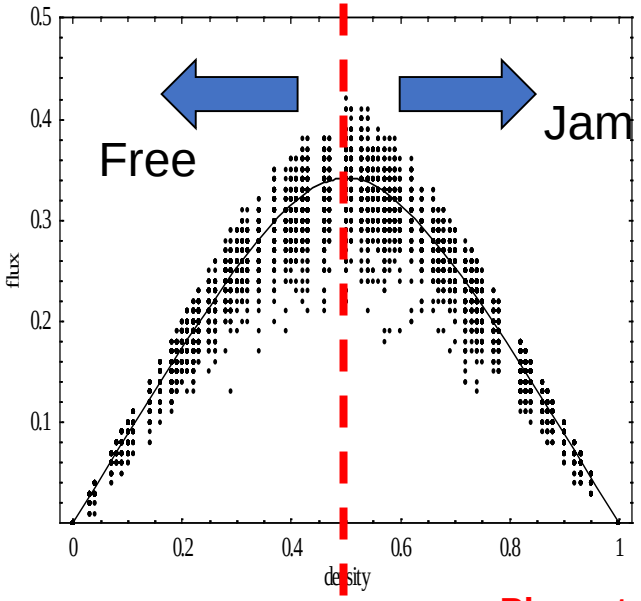
K. Nishinari, et al, IEICE Trans. Inf. & Syst. (2004) p.726

The model reproduces the phase transition of “Jamming”.

Fundamental Diagram

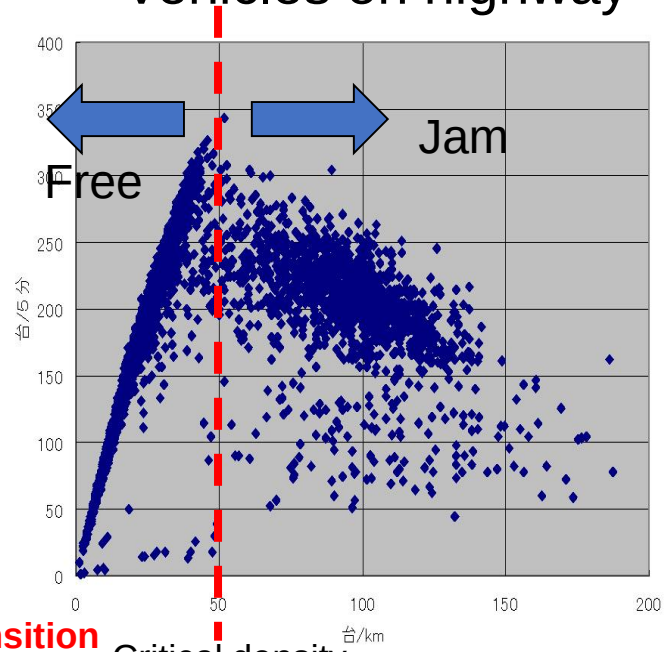


ASEP



Critical density

Vehicles on highway



Critical density

Phase transition

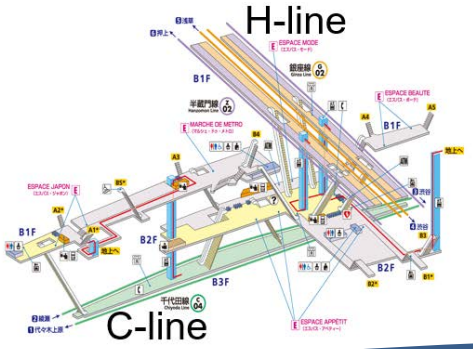
This curve is common among various kinds of SDP!

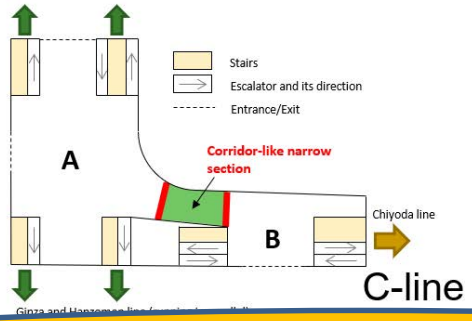
Application

Reducing congestion at a Tokyo Metro station

- Omote-Sando station
- 150,000 passengers /day
- Change trains here from/to Hanzomon to/from Chiyoda line

Tokyo Metro Station





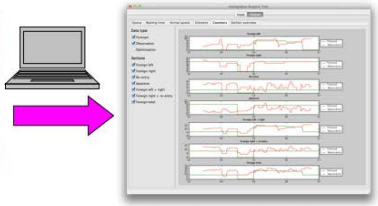
Areas with potential risks

- **Bottlenecks**
  In the bottleneck part, Flow balance collapses and crowded.
  →Signage is strictly prohibited.
- **Stairs**
  Speed difference (reduced to half by stairs)
- **Escalator**
  Speed difference
- **Corners**
  Counter flow collision
- **Merging**
  Flow increases and becomes complicated
  High density + cross-intersection is dangerous!

Crowd control: jamming, panic, emergency, terrorism,…

Airport

by prediction of arrival passengers at the area



- Flight info
  arrival time
  number of passengers

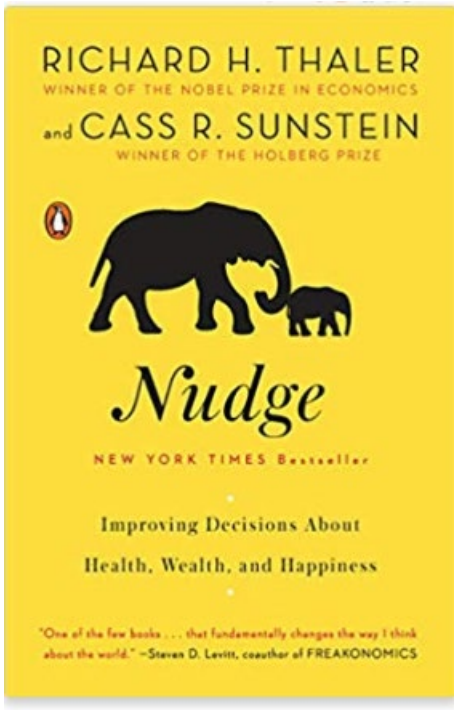
Optimization of # of counters to minimize the waiting time for passengers

- customer satisfaction
- reduction of walk for staffs

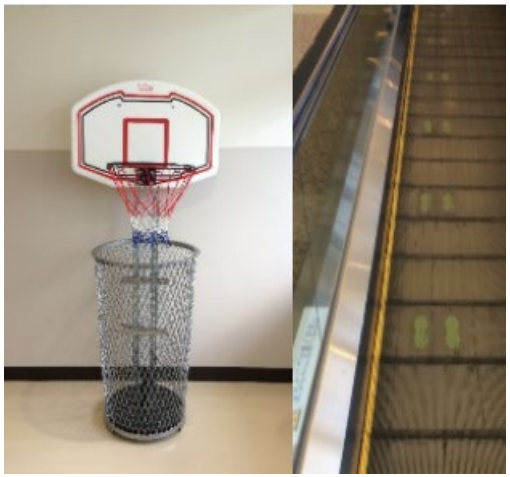
Nudge theory

ELSI

Do not enforce a **rule**, but let them behave **naturally.**



- **Light**: People move toward the lighter direction
- **Sound**: Synchronous behavior with rhythm
- **Infrastructure**: Affordance



Ref: Naohiro Matsumura
「ひじでつく」ナッジ，「そそる」仕掛け

Nudge theory is a flexible and modern change-management concept for understanding of how people think, make decisions, and behave; helping people improve their thinking and decisions; managing change of all sorts and; identifying and modifying existing unhelpful influences on people.

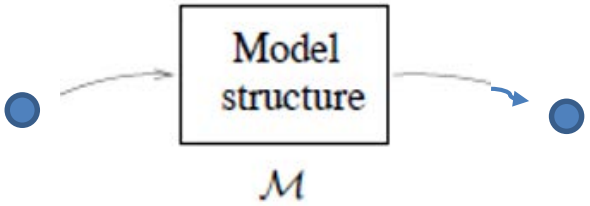
Uncertainty Quantification (UQ) and Data Assimilation (DA)

All WGs

What are UQ and DA?
Why such a framework is useful?

- Uncertainties are unavoidable in real-world problems.
- PDF (probability distribution function) is approximate to describe and control the uncertainties.
- Data gives us a chance to improve the evolution of PDF (This is DA!)
- Propagation and control of uncertainties are possible via UQ with Bayesian techniques.

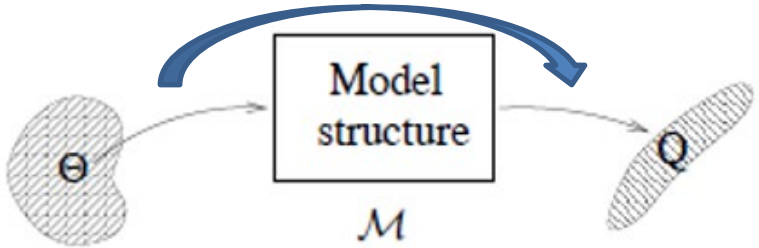
Deterministic Model



Dirac-δ ➔ Dirac-δ

Probability distribution Model

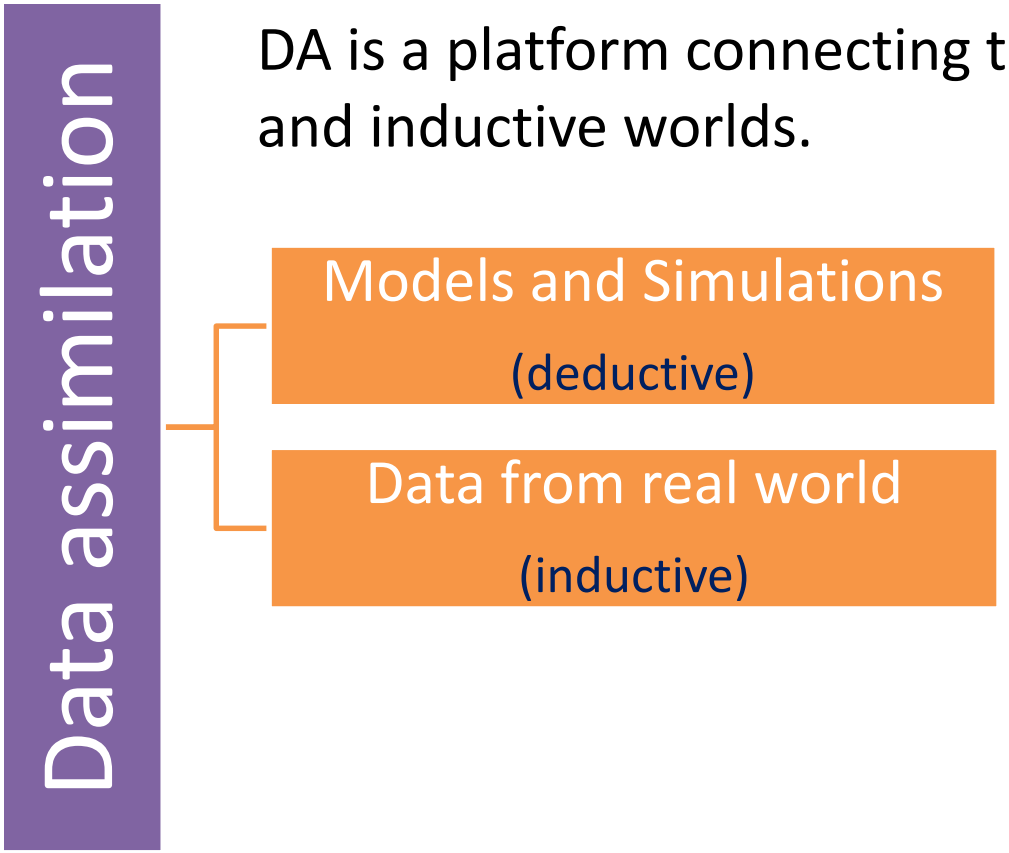
Forward UQ (simulation)



Instead of a single predicted value, we obtain information about the range of values that Q may have in light of uncertainty

Once data is given, then we have a new PDF (new knowledge) : **prediction** via Bayesian Filter

What is DA?



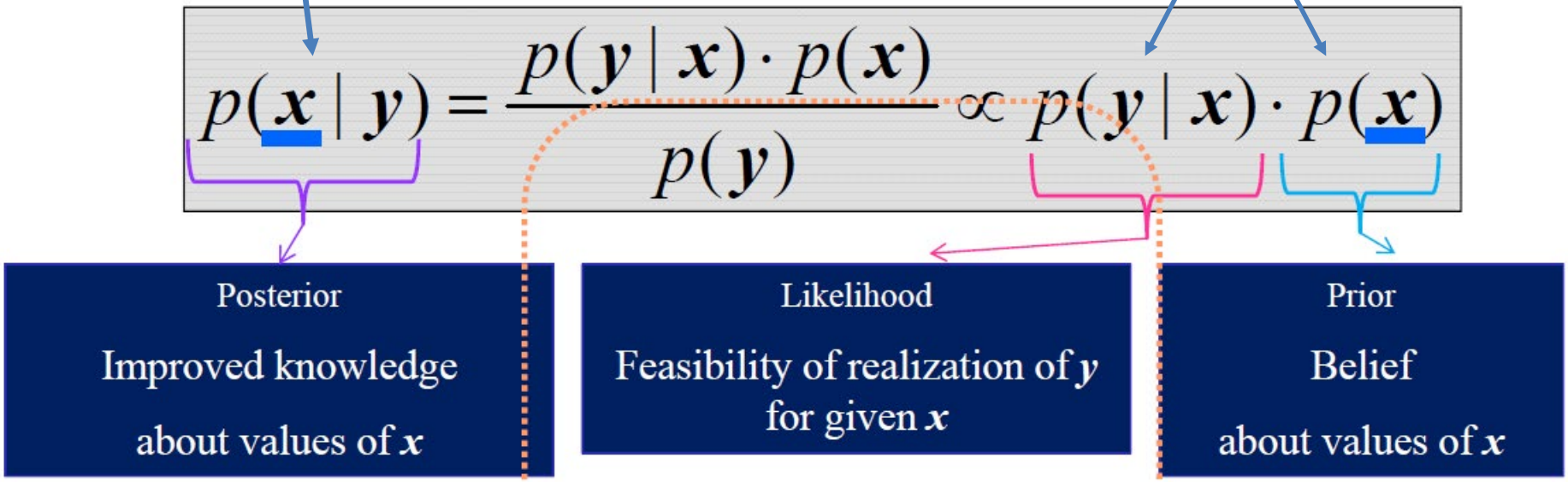
DA is a platform connecting the deductive and inductive worlds.

Bayes' Theorem

x : **What we are interested in. (cause)**

y : **Data (result)**

Backward UQ (new knowledge) **Forward UQ** (simulation)



$$p(y) = \sum p(y \mid x)\, p(x)$$

The curse of high-dimensionality

- Models are usually quite **high**-dimensional
- **Massive** Data from monitoring device

- Computations become intractable!
- Dynamical system approach comes in.
  - Reduction to **low** dimensional systems
  - Lagrangian data assimilation works!

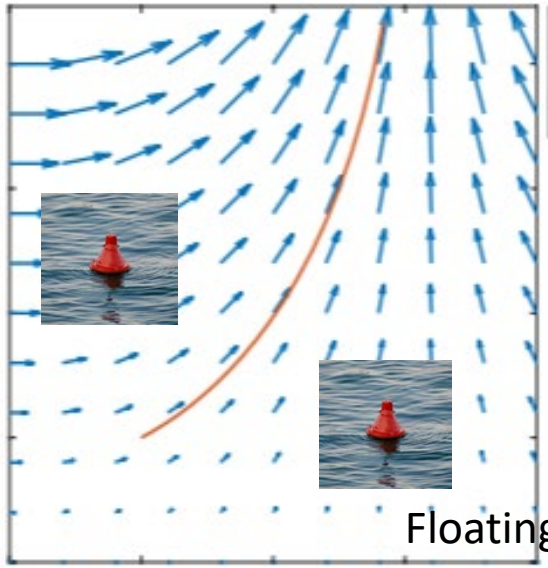
Lagrangian manifold

MORE AT SIAM

siam news

HOME | HAPPENING NOW | GET INVOLVED | RESEARCH

SIAM NEWS JULY/AUGUS



Print

Research | July 19, 2(

Chris Jones

Lagrangian Modeling

By Christopher K.R.T. Jone

Floating buoys converge to the manifold.

In making predictions or estimations of the state of a system, in our case the ocean, uncertainty is derived from many sources. There are errors in the model, as it cannot reflect reality fully, but also in the observations, because of instrument inaccuracies, human error, and the processing of the information. It is particularly important to consider observational errors in ocean studies, in which so much of the data collection is indirect: Model variables, such as fluid velocity, are estimated from measurements made at sea-surface height; gliders measure temperature and density, but their locations are not known exactly.

Reducing the uncertainties is crucial for early decision-making

- When rivers start to flood?
- When evacuate a home?
- Where is the safer place?

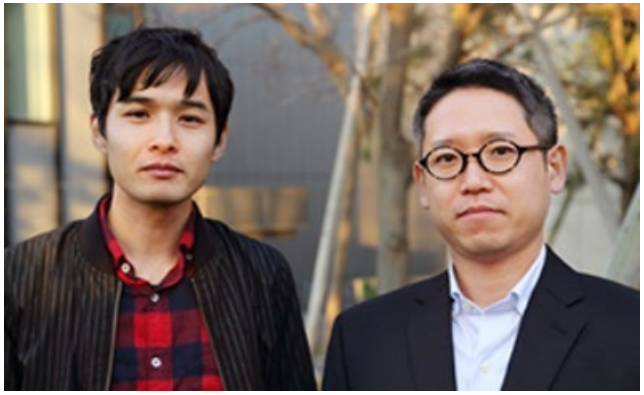
October 2019, Typhoon Hagibu attacked Honshu and Kanto areas

Residential areas flooded by the Chikuma River are shown in this bird's-eye view after Typhoon Hagibis tore through Nagano on Saturday. | REUTERS

NATIONAL

At least 35 killed and 17 missing after Typhoon Hagibis tears through country, flooding rivers and submerging cities

Smart and quick prediction for extreme events



CREST

Big Data: Applications

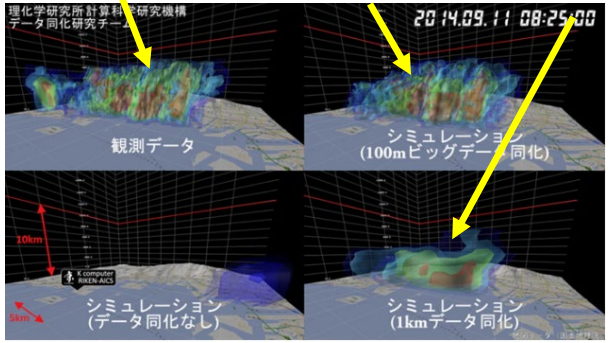
T. Miyoshi's group

Jan. 18, 2018

Himawari-8 data assimilated simulation enables 10-minute updates of rain and flood predictions

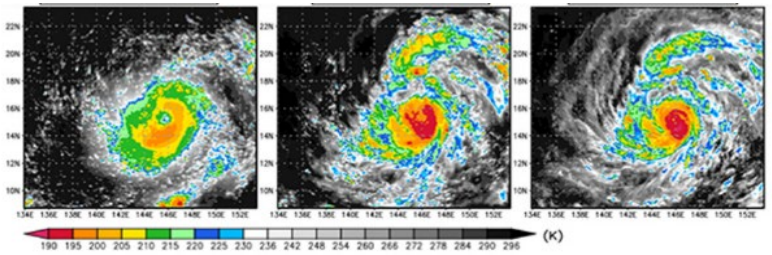
Real date　　Simulation with DA

No DA



Typhoon

No DA,　　With DA,　　Real data from a satellite



Predict the location of extreme heavy rain within 30minutes.

Pandemic

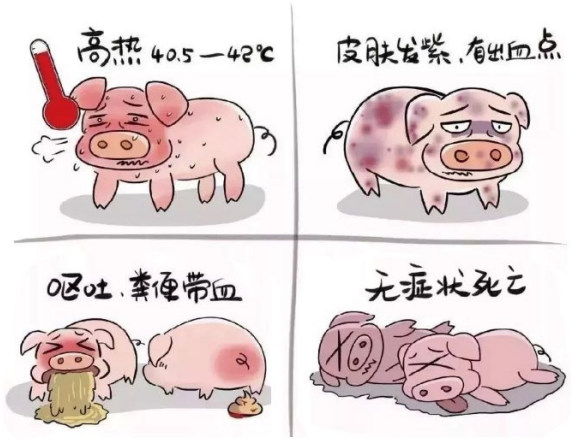
WG 1, 2

African Swine Fever in China

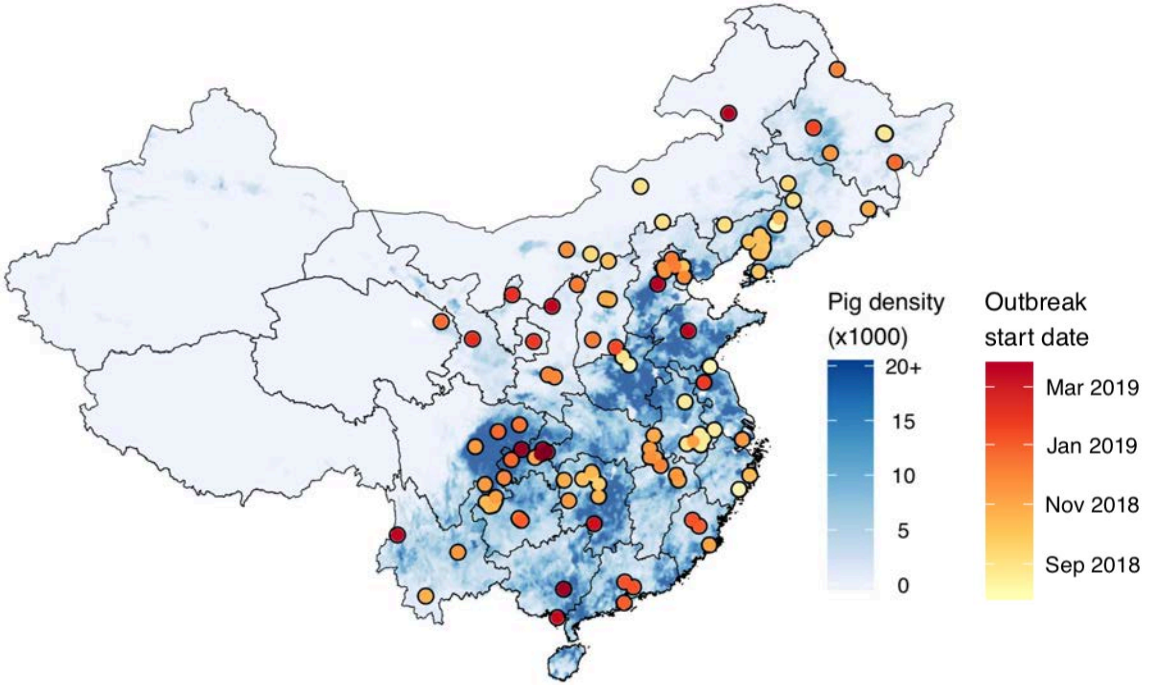
Hiroshi Nishiura

PRESTO sakigake CREST

High fever, loss of appetite, depression, weakness, red & blotchy skin or skin lesions, vomiting, diarrhea, coughing, sudden death



[USDA]



- Swill feeding
- Contaminated vehicles & equipment
- Feral swine
- Contaminated feed
- Sick pigs
- International travelers
- Contaminated clothing & shoes

Endo PhD candidate at LSHTM, SIR model with immunity level

Contents lists available at ScienceDirect

Annals of Epidemiology

journal homepage: www.annalsofepidemiology.org

Original article

Capturing the transmission dynamics of the 2009 Japanese pandemic influenza H1N1 in the presence of heterogeneous immunity

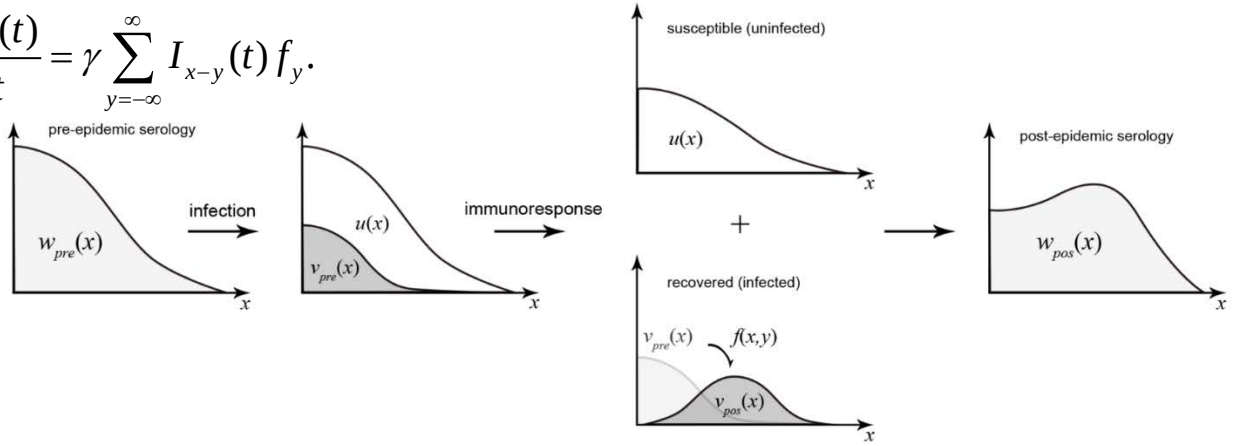
Akira Endo, MD [a,b], Keisuke Ejima, PhD [c], Hiroshi Nishiura, MD, PhD [a,b,*]

$$\frac{dS_x(t)}{dt} = -\beta_x S_x(t) \sum_{y=-\infty}^{\infty} I_y(t),$$

$$\frac{dI_x(t)}{dt} = \beta_x S_x(t) \sum_{y=-\infty}^{\infty} I_y(t) - \gamma I_x(t),$$

$$\frac{dR_x(t)}{dt} = \gamma \sum_{y=-\infty}^{\infty} I_{x-y}(t) f_y.$$

A simply looking conceptual model works efficiently !



Robotics

WG 3

Move before think

Novel Control Principle Facilitated by Interactions with the Environment


Kobayashi


Ishiguro


Aonuma


Osuka

Question:

Why don't we have robots moving around in natural environments or everyday space ?

Why not only higher animals but also lower animals can do that ?

	Conventional Control		Animals' Control	
Works well in factory but not in nature	Search environment completely High accuracy in the closed frame **Think before move**	⇔	No way to know environment completely Robust in the open world **Move before think**	Worked well in billions of years

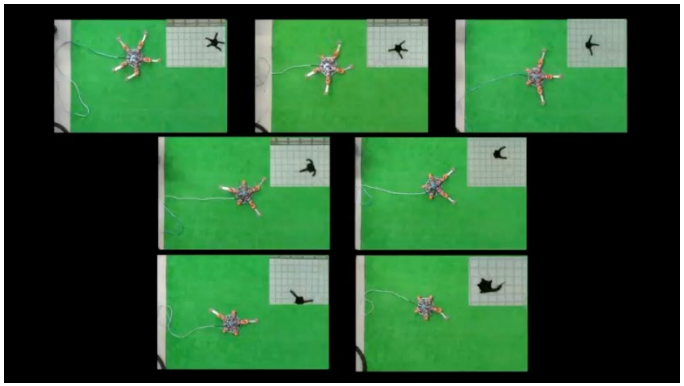
Mobile robot must follow this way

Three Key Concepts

- Hierarchical Control — Decentralized control + Centralized control
- "Tegotae" Control — Dialogue between robot and environment
- Ying-Yang Control — Implicit control + Explicit control

CREST


Brittle Star


Super resilience is achieved by TEGOTAE control


Centipede

Locomotion in nature by pure implicit control

Locomotion by pure implicit control!

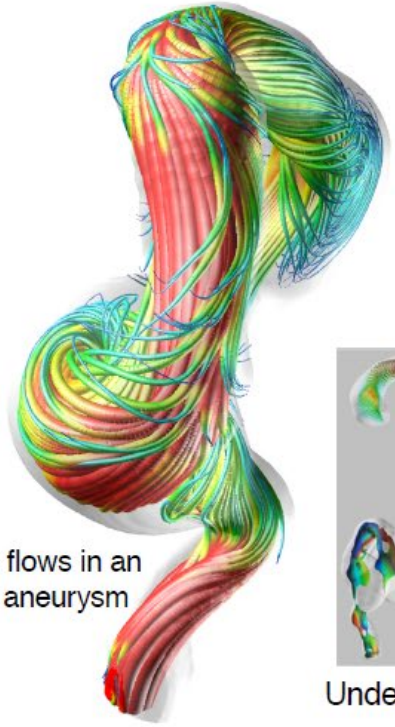
Cardiovascular problem

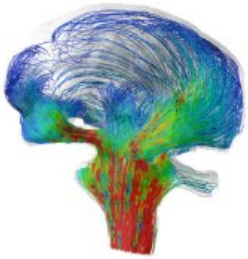
WG 1, 2

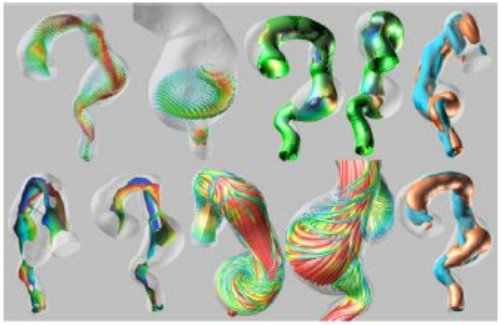
Collaboration with Clinical Medicine

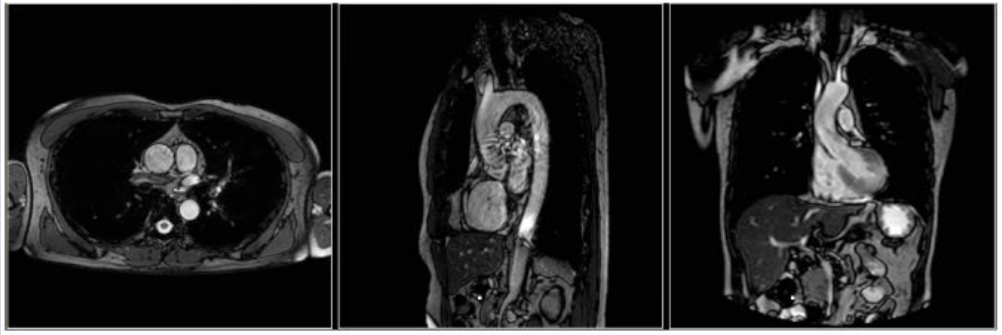

Suito

JST MIRAI PRESTO sakigake CREST


Blood flows in an aortic aneurysm


Cerebrospinal fluid flow


Understanding blood flow structures

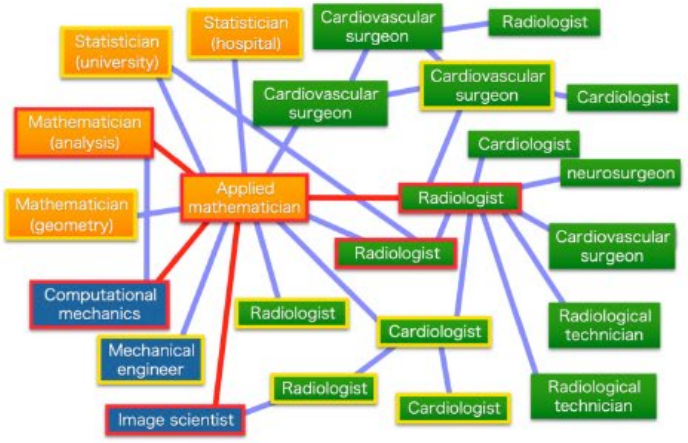

Medical imaging technologies

Proper setting for clinical questions

Appropriate setting for mathematical modeling

Goals

- Understanding disease mechanisms
- Provide new view points and algorithms
- Medical image diagnosis/detection
- Statistical analysis for EBM



Researchers network spreading from pure mathematicians to clinicians

Extract decision algorithms from implicit knowledge of specialists

Mathematics Humanities

WG7

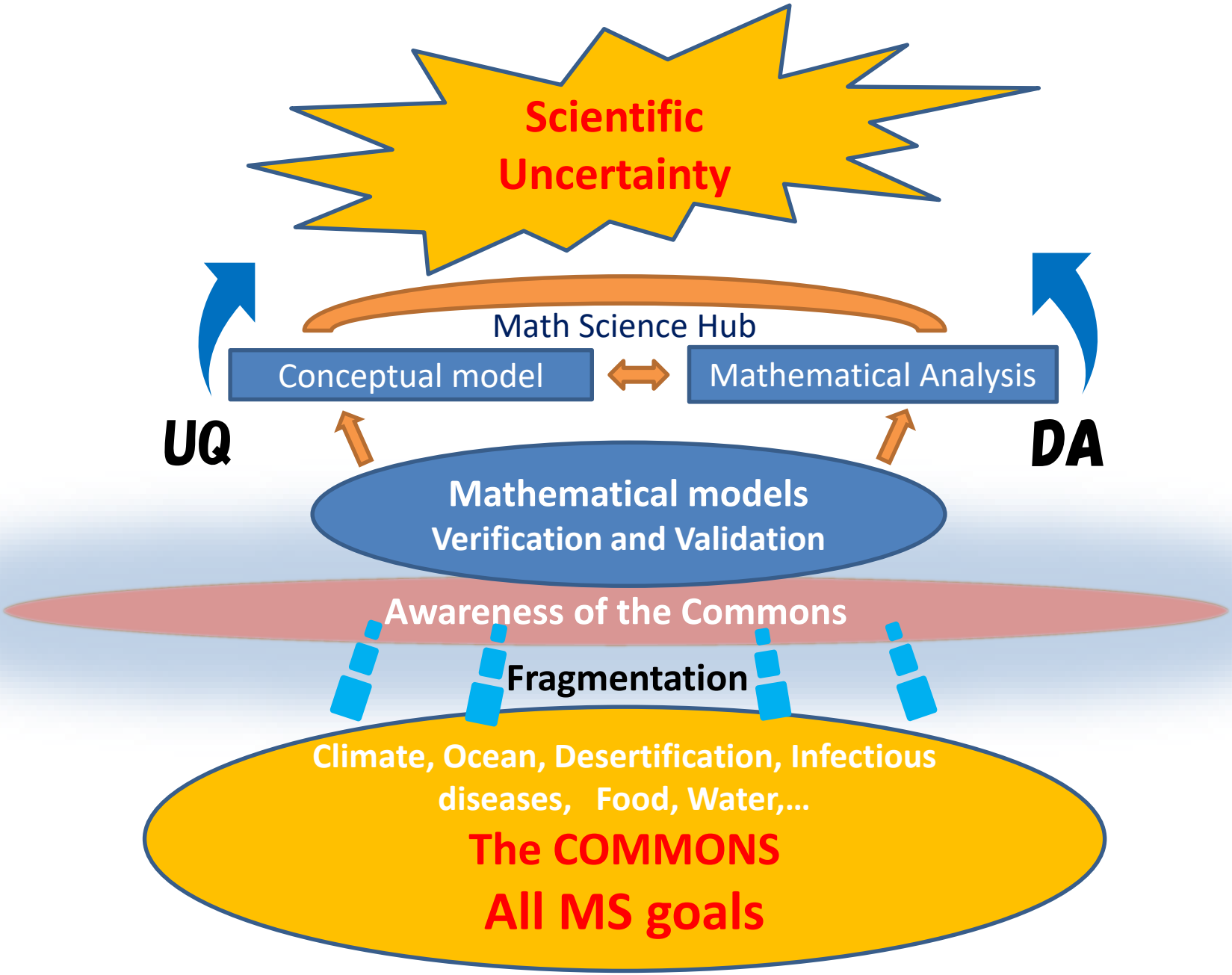
Living with “the commons” is a key to the Moon Shot program

By “the commons” I mean those assemblages and **ensembles of resources that human beings hold in commons** or in trust to use on behalf of themselves, other iving human beings, and past and **future generations** of human beings, and which are essential to their biological, cultural, and social reproduction. (Nonini 2006)

Satoshi Machidori (Kyoto Univ)

Shigeki Uno (Tokyo Univ)

“The Commons in the modern society”
- Beyond the Publicness”-


Scientific Uncertainty
Math Science Hub
Conceptual model
Mathematical Analysis
UQ
DA
Mathematical models
Verification and Validation
Awareness of the Commons
Fragmentation
Climate, Ocean, Desertification, Infectious diseases, Food, Water,…
The COMMONS
All MS goals

Untangle VUCA

- Clarify the meaning of "Uncertainty" scientifically and try to resolve skepticism.
  - That's a toy model in silico, nothing to do with the reality.
  - I am more interested in how to survive today, not tomorrow.
- Recover reliability of scientific approaches.
  - The predictive power has been so much enhanced based on improved math models and computational power.
- Extract the fundamental mathematical scheme common to these issues.
- Create a new mathematical science hub for the Commons.
- Awareness of the Commons for students and young researchers including the field of humanities.

Functioning of Mathematics

- Recognizable : Common stage
  - Visible by mathematical language
    - Sometimes in a counter-intuitive way!
- Reduction : Allows us to handle complex issues
  - Compression with keeping essential features (avoid the curse of high-dimensionality)
    - Sometimes we extend it to **infinite** dimension (completely opposite way!)
- Predictable : Make the future a better place
  - Manipulate computable objects in a reliable way
    - Reliable modeling with data assimilation

Thank you for listening!